Athletic Assistive Technology for Persons with Physical Conditions Affecting Mobility

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ABSTRACT

Recent advances in technology have allowed athletes with physical conditions to perform at increasingly high levels. After the ruling that one such athlete had an advantage over “able-bodied” athletes before the 2008 Olympics, many question whether these technological advances have even augmented athletic abilities. Although much progress has been achieved, technology for “disabled” athletes must be far advanced to allow them to reach and surpass the ability level of able-bodied athletes. Here, we review the current state of assistive devices created to assist athletes with physical conditions affecting their mobility. We form a quantitative comparison between athletes with and without physical conditions, lay out recent advancements in the development of sports-related assistive devices, and discuss the implications of these devices. Using the Paralympics as a guide, this work serves as an overview of the current state of assistive technology for athletes with mobility conditions and a tool for future researchers attempting to bridge the gap between athletes with and without physical conditions. (J Prosthet Orthot. 2014;26:154–165.)

KEY INDEXING TERMS: assistive technology, prosthesis, wheelchair, sports, Paralympics, athletes with physical conditions, athletes with mobility conditions, disability

In 2008, the International Association of Athletics Federations (IAAF) began a worldwide debate when they established Rule 144.2(e), prohibiting the use of technical devices that offer a competitive advantage. Specifically citing springs as advantageous, this rule resulted in the immediate disqualification of Oscar Pistorius, the South African bilateral amputee sprinter vying to become the first amputee to compete with “able-bodied” runners at the highest level. Extensive trials and investigation resulting from this ruling caused its eventual repeal, allowing Oscar Pistorius to make history as the first-ever amputee sprinter to compete in the Olympics. The initial verdict evoked some pivotal research in sports performance enhancement for athletes with mobility conditions (AMCs), and a rather interesting question emerged:

Just how far can assistive technology enhancements take all athletes in the future?

To examine this question, in this article, we explore the current state of para-athletics, surveying the literature to assess the present achievements of AMCs, and find recent advances in assistive technology for sports-related applications. This exploration provides insight into the current direction of assistive device developments, which could contribute to a future wave of augmentative devices.

CONTRIBUTION

Disability is an umbrella term often used to describe a physical or mental impairment that substantially limits one or more major life activities and causes participation restrictions for an individual. However, using any form of this term to refer to humans is unacceptable because the ability to perform at extraordinary levels can be restored given the right technology, as evidenced by Oscar Pistorius. The focus of this work is athletes with physical conditions, specifically conditions that affect limb and motor function. We discuss current work on technology that assists these athletes, thus directly addressing activity and participation restrictions and improving the athlete’s ability to perform. The goal is to outline current design approaches, evaluating their efficacy and potential for future applications.

PREVIOUS WORK

Sports for AMCs have made great strides since the inception of the Paralympics approximately a half century ago. Within the last 2 decades, the Paralympics and the Olympics became more closely tied, resulting in a sudden surge in exposure and popularity, as well as newfound “disabled” star athletes. Since then, much work has gone into studying sports performance of AMCs from a variety of angles. Although many focus on the Paralympics and its history, others cover topics ranging from psychological characteristics of para-athletes to sociopolitical implications of para-athletics.

One of the major concerns in all sports is injury. Medical professionals and athletes alike are deeply invested in studying the occurrences, causes, prevention, and diagnosis of injuries. In 2009, Miller investigated medical issues associated

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with Paralympians, discussing common injuries and illnesses encountered by these athletes. Mason furthered this discussion in 2012 when he reviewed the history of sports medicine for AMCs, forming one of the most comprehensive assessments of AMC sports medicine to date. Others have examined specific occurrences of injury to uncover where and how AMCs are most vulnerable.10-14

Psychological factors affecting AMC sports performance have been studied extensively as well. Evaluations of self-esteem, happiness, and other psychological factors arose as early as the 1980s, showing that there are mental benefits of sports participation for persons with physical conditions. More recently, Martin found that sport experience positively affected motivation for youth with physical conditions. Other reviews by Jefferies et al., Deans et al., and Martin emphasize the growing importance of sports psychology for AMCs. As a result, new methodologies for providing sufficient psychological assessments to AMCs by sports psychologists have arisen.

Social and political issues are the focus of an overwhelming majority of publications concerning athletes with physical conditions. Often, these are related to civil rights, accessibility, and unfair treatment. One such example is the disparity in media coverage for para-athletes when compared with able-bodied athletes. Traditional media sources have failed to give equal coverage to AMCs, and when they do, the language used has commonly been perceived as negative and offensive. Further, some have criticized the "disempowerment" of para-athletes underlying the structure of competition. A clear separation from the Olympics, substantial funding differences, and disparate media coverage make the Paralympics, and equivalently AMC sports, less inclusive than it is often stated and intended to be.

To our knowledge, few academic publications have reviewed assistive technology for AMCs. Burkett recently conducted two such reviews, one examining technology used exclusively in summer Paralympic competitions and a secondary piece focusing on technology for the winter Paralympics. In addition, briefly discussed assistive sports technology in a 2012 review of prostheses and artificial skins. Previous studies of assistive devices for sports mostly focus on prostheses or exclusively Paralympic technology. Here, we review the current state of para-sports performance and many devices built to aid athletes with mobility conditions, using the Paralympics as a starting point and method for evaluating the impact of assistive technology.

**PARA-ATHLETE PERFORMANCE**

One way to evaluate the current state of para-sports performance is to assess the Paralympic Games, analyzing its history and comparing it with the Olympics. Although International Paralympic Committee (IPC) regulations, which have the potential to limit improvements in athletic performance, prohibit the use of certain assistive devices, this analysis does offer some indirect insight into the state of assistive sports technology and its ability to facilitate world-class athletic achievement. The Paralympics is the Olympic-equivalent worldwide sports competition for athletes with conditions that affect athletic ability. It officially began in 1960. Now, it occurs immediately after the Olympics every 4 years and in the same city. Examining Paralympic events gives clues to which assistive technologies are most advanced and useful for athletic activities. Further, comparing the top performances in the Paralympics and the Olympics gives a more quantitative measure of the efficacy of these technologies in matching biological performance.

The Paralympics features 26 distinct events, ranging from aquatics to wheelchair tennis. Of these, 23 coincide with Olympic events (see Table 1). Observing the absence of certain Olympic sports in the Paralympics offers some obvious key distinctions. Specifically, more dynamic sports with varied movements seem to be the most difficult to reproduce, especially combat sports. Even those represented in the Paralympics can be achieved only through the use of wheelchairs. Perhaps, this underscores the present shortcomings in prosthetic devices, which tend to be most powerful for single-plane movements.

Further disparities can be seen in the world records posted in the two competitions. The IPC tracks records only in four sports: athletics, powerlifting, shooting, and swimming.

<table>
<thead>
<tr>
<th>Olympics</th>
<th>Olympics and Paralympics</th>
<th>Paralympics</th>
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<tbody>
<tr>
<td>Badminton</td>
<td>Aquatics</td>
<td>Boccia</td>
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<td>Bobsleigh</td>
<td>Archery</td>
<td>Goalball</td>
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<tr>
<td>Boxing</td>
<td>Athletics</td>
<td>Wheelchair dance*</td>
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<td>Golf</td>
<td>Basketball*</td>
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<tr>
<td>Gymnastics</td>
<td>Biathlon</td>
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<td>Handball</td>
<td>Canoe/kayak</td>
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<td>Hockey</td>
<td>Curling*</td>
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<tr>
<td>Luge</td>
<td>Cycling</td>
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<tr>
<td>Modern pentathlon</td>
<td>Equestrian</td>
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<tr>
<td>Skating</td>
<td>Fencing*</td>
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<tr>
<td>Taekwondo</td>
<td>Football</td>
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<tr>
<td>Wrestling</td>
<td>Ice hockey</td>
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<td>Rowing</td>
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<td>Rugby*</td>
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<td>Sailing</td>
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<td>Shooting</td>
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<td>Table tennis</td>
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<td>Tennis*</td>
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<td>Triathlon</td>
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<td>Volleyball</td>
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<td></td>
<td>Weightlifting</td>
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</table>

The first column displays competitions that are performed only in the Olympics. The second column shows events that are performed in both the Paralympics and the Olympics. The third column shows events that are performed in the Paralympics but not in the Olympics. *Wheelchair-only events in the Paralympics.
Table 2 lists select aquatics and athletics records and compares para-athlete records with equivalent Olympic athlete records. In the Paralympics, competitors are classified on the basis of ability level and/or condition type. Broadly speaking, the IPC recognizes six condition categories: amputee, cerebral palsy, intellectual, wheelchair, visual, and leautres.31 Classifications differ in every sport and follow a set of guidelines established and maintained by the IPC. Examples are shown in Table 2 and are defined as follows:

Aquatics
(numbers move from least ability to most ability)
1 to 10: Physical
11 to 13: Visual
14: Intellectual

Athletics
11 to 13: Blind/visual
20: Intellectual
32 to 38: Cerebral palsy (32–34 wheelchairs, 35–38 ambulant)
40 to 46: Amputation or other condition such as dwarfism (ambulant)
51 to 58: Spinal cord injury or amputation (wheelchair)

Apparent differences exist within the classes of para-athletes and between athletes with and without physical conditions. These are highlighted by record comparisons (see Table 2). Quickly, one can see which conditions affect performance most severely. In particular, athletes with intellectual conditions seem to be affected the most, with world records reported only for six athletic and aquatic events. No other condition affected athletic performance as drastically as intellectual conditions; however, ability level is directly linked to the degree and type of condition and differs for every sport.

Aquatic records follow in an order most would expect. In all cases, para-athletes post slower records than Olympic athletes. Differences in these records tend to increase with race distance. For example, in short 50-m races, high-level para-athletes fall short of Olympic athlete record times by just greater than 2 seconds (10%), showing that these athletes perform at an elite level despite the condition. However, as races become longer, the disadvantages of para-athletes begin to show more. Eventually, record time spreads increase to nearly 2 minutes (13%).

On the other hand, athletics records are more interesting. Although they mostly follow the trends seen in aquatics competition, there are a few unexpected observations. As one would anticipate, athletes without conditions typically outperform para-athletes, especially in jumping and throwing events. However, a trend begins to arise in longer races (i.e., 800, 1,500, 5,000, and 10,000 m). In these races, some para-athletes have exceeded Olympic athlete times. The most drastic example of this occurs in the 10,000-m race, when the fastest para-athlete outperformed his Olympic athlete counterpart by greater than 6 minutes (25%). Although this seems counterintuitive at first glance, upon reviewing the Paralympic classifications (see above), one can notice that each of these high-performing para-athletes competes using a wheelchair. This gives rise to two key observations about para-sport and the assistive devices that facilitate them: 1) wheelchairs are currently the most effective and versatile assistive devices and 2) all assistive devices fall short of consistently reproducing natural athletic ability.

**DESIGN APPROACHES**

Designs of assistive devices for athletic activities depend mostly on the sport, with each differing in the desired tasks and goals. With this in mind, the following review of assistive device design approaches is organized according to the general task and/or sport. The section is split into five major subsections: wheeled mobility, ambulatory mobility, nonwheeled seated sport, snow and ice mobility, and aquatic mobility. Wheeled mobility covers advances in manual wheelchairs, cycling, and powered wheelchairs. Ambulatory mobility includes recent developments in running and jumping devices for athletes with lower-limb conditions. The nonwheeled seated sport subsection discusses commonly used devices for seated track-and-field sports as well as fishing. Snow and ice mobility covers skiing and snowboarding technology. Finally, aquatic mobility discusses assistive technology for swimming and rowing.

**WHEELED MOBILITY**

Manual wheelchairs are the most widely used assistive devices for athletes with ambulatory conditions by a substantial margin. Sports conducted with them include tennis, rugby, curling, and dance, to name a few. When compared with other devices, they tend to be more versatile and effective. Their widespread use has led to a number of dedicated publications.32-36

Years of work have gone into creating ergonomic wheelchair designs.32 To accomplish this, wheelchairs are tweaked to be lighter, faster, and more maneuverable. Advances in materials and mechanisms have made this possible. Typical wheelchairs consist of several customizable components, including the frame, seat, and wheels. Each one affects performance. Light frames are essential for acceleration and upper-limb preservation, seat cushions provide pressure relief for sustained use, hand rims govern control and propulsion tasks, and casters and straps provide stability.36-38 Further, wheel orientation/camber (Figure 1A) has been shown to affect maneuverability,34,36,41 and seat orientation (Figure 1A) influences stability and control.34,36 Decisions regarding these parameters differ on the basis of sport.

Component tweaks, as described above, account for most sport wheelchair design decisions. Although the decisions to be made remain the same, the methods for determining them differ, with some even developing novel devices and experiments to decide.42 Others have explored dedicated designs for specific communities.43-45 Berger et al.43 designed a wheelchair for basketball players in the Netherlands with a redesigned frame to reduce weight and increase strength and an altered wheel position, angled in such a way that tire deformation is eliminated without sacrificing maneuverability.
Advanced wheelchairs are often quite expensive, limiting their use to more wealthy countries and individuals. To combat this, Authier et al. developed a low-cost sport wheelchair for developing nations. Wheelchair development and selection both require a specialized and customizable approach based on body type, activity, and even location.

Para-cyclists have a choice of four different types of cycles: tandem cycles, tricycles, bicycles, and hand cycles. They all offer distinct advantages and disadvantages, which depend on the activity and the condition of the user. Tandem bikes are made for two riders. There are two seats and two sets of handlebars. Athletes with visual conditions use these; the athlete sits at the back and a “sighted pilot” guides from the front. Athletes with balance deficiencies use tricycles. The extra wheel eases balance, allowing athletes to stabilize in a way that they cannot on two wheels. Athletes with mobility conditions use

Table 2. Men’s aquatics and athletics world records

<table>
<thead>
<tr>
<th>Event</th>
<th>Paralympics</th>
<th>S1–S10</th>
<th>S11–S13</th>
<th>S14</th>
<th>Olympics</th>
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<tbody>
<tr>
<td>50-m Freestyle</td>
<td>0:23.16</td>
<td>0:22.99</td>
<td></td>
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<td>0:20.91</td>
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<tr>
<td>100-m Freestyle</td>
<td>0:50.87</td>
<td>0:50.91</td>
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<td>0:46.91</td>
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<tr>
<td>200-m Freestyle</td>
<td>1:54.46</td>
<td>1:56.78</td>
<td>1:58.42</td>
<td>1:42.00</td>
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<tr>
<td>400-m Freestyle</td>
<td>4:04.20</td>
<td>3:58.78</td>
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<td>3:40.07</td>
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<tr>
<td>1500-m Freestyle</td>
<td>16:24.63</td>
<td>16:33.79</td>
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<td>14:34.14</td>
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<tr>
<td>50-m Backstroke</td>
<td>0:28.42</td>
<td>0:27.57</td>
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<td>0:24.04</td>
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<tr>
<td>100-m Backstroke</td>
<td>1:00.01</td>
<td>0:56.97</td>
<td>1:01.85</td>
<td>0:51.94</td>
<td></td>
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<tr>
<td>200-m Backstroke</td>
<td>2:15.04</td>
<td>2:18.10</td>
<td></td>
<td></td>
<td>1:51.92</td>
</tr>
<tr>
<td>50-m Breaststroke</td>
<td>0:29.16</td>
<td>0:29.90</td>
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<td>0:26.67</td>
</tr>
<tr>
<td>100-m Breaststroke</td>
<td>1:04.02</td>
<td>1:03.91</td>
<td>1:06.69</td>
<td>0:58.58</td>
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<tr>
<td>200-m Breaststroke</td>
<td>2:24.23</td>
<td>2:33.82</td>
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<td>2:07.01</td>
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<tr>
<td>50-m Butterfly</td>
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<td>0:24.53</td>
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<td>0:22.43</td>
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<tr>
<td>100-m Butterfly</td>
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<td>200-m Butterfly</td>
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<td>2:13.40</td>
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<tr>
<td>200-m Butterfly</td>
<td>1:51.51</td>
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IPC. The far left column displays events. The middle columns display world records set by para-athletes. They are split on the basis of classification. For aquatics, lower numbers generally indicate less ability, whereas higher numbers indicate more ability. The columns are split on the basis of three separate classifications: physical conditions (1–10), visual conditions (11–13), and intellectual conditions (14). Athletics competitors are split into five classes: blind/visual conditions (11–13); intellectual conditions (20); cerebral palsy (32–38); wheelchair (32–34) and ambulant (35–38); amputation or other conditions such as dwarfism, ambulant (40–46); and spinal cord injury or amputation, wheelchair (51–58). The far right column displays world records set by athletes eligible for the Olympics.
standard bicycles, if possible. These follow the standard design, but slight modifications are sometimes made to meet the needs of the condition. Many of these modifications involve custom attachments between the rider and the bike. Finally, hand cycles are operated by hand instead of foot. Usually, the rider assumes a kneeling or lying position. We focus only on hand cycles because either the others are beyond the scope of this article or limited innovation exists specifically for AMCs.

Hand cycles share many of the same design goals as wheelchairs. Like wheelchairs, hand cycles have progressed with materials and designs. Further, custom component layouts are used to optimize individual performance. This versatility can be seen in Siebert’s work on an adjustable chassis for a mountain hand bike. As shown in Figure 1B, Siebert alters the tire layout and builds completely adjustable cranks, footrests, backrests, brackets, and drive trains to allow total customizability in off-road conditions.

Hand cranks are unique to hand cycles and a major source of customization. Many have studied the performance differences caused by altering them. These studies typically revolve around mechanical efficiency and power effects. Crank length was studied by Goosey-Tolfrey et al., who determined that shorter crank lengths tend to be more efficient. Further, Krämer et al. analyzed the effects of crank angle and width on performance in two separate articles, revealing that a more pronated handle offers improvements, whereas width has minimal influence. Arnet et al. found that an upright backrest with a distant crank position reduces shoulder load. Finally, van der Woude et al. measured the effects of gear ratio and mode on propulsion characteristics and observed a significant reduction in metabolic expenditure during synchronic arm use with lighter gear ratios. Hand cranks are a key component of hand cycles, and, as such, their development over the years has led to enhanced ability.

Powered assistive sports devices are extremely uncommon. This makes sense for competitive sports, but for recreational sports, these are needed to promote activity among populations with the most serious conditions. So far, the most common powered devices used for sport are paramobile devices, those that mobilize paraplegics. These often assist in sitting-to-standing transitions, and although this may sound minor, it allows paraplegics to take part in less rigorous standing activities, such as golf. Figure 1C displays this transition. The most common commercial paramobile devices resemble

Figure 1. Manual wheelchair, hand cycle, and paramobile device. A, Wheel camber is the orientation of the wheel relative to the frame (left column). Positive camber (bottom left) creates a larger base of support and improves lateral stability, hand-rim comfort, and maneuverability. However, positive camber also increases rolling resistance, decreases seat height, and enlarges footprint/turning radius. Seat angle is the orientation of the seat relative to level ground (right column). Seat dump (bottom right) improves lateral stability and hand-rim accessibility, but it decreases rearward stability and height. Both wheel camber and seat angle should be chosen appropriately to optimize individual performance, balancing their positive attributes with the negative. B, A hand cycle with an adjustable chassis allows the rider to adapt to off-road conditions. C, A paramobile device for paraplegics facilitates upright posture useful for golfing. Adapted from Goosey-Tolfrey, Siebert, and Wucherpfennig and Boyer.
Perk’s upright wheelchair and use a motorized, tiltable seat that erects the rider in a manner suitable for swinging a golf club.

**AMBULATORY MOBILITY**

With Oscar Pistorius’ success in the 2012 Olympics came much coverage of lower-limb prostheses, both as praise and criticism. Some argue that state-of-the-art lower-limb prostheses offer amputee athletes distinct advantages when compared with their able-bodied counterparts. These sentiments do make a statement about the progress that ambulatory prostheses have encountered in recent years; however, they overlook the progress that remains to be made. This potential for future development is highlighted by the large amounts of work still being conducted to further develop running prostheses. Table 1 shows that wheelchairs are still a very common tool for athletes with ambulatory difficulties. Future developments in ambulatory prostheses for athletes seek to open up opportunities for nonwheelchair athletes that are currently unavailable. Here, we discuss recent developments.

Passive running prostheses have progressed with materials. Because modern advances in materials have caused them to become lighter but stronger, prostheses using these materials can withstand a higher load demand while not inhibiting the wearer because of weight. In addition, recent innovation has seen these devices become more biomimetic, but not in appearance. Running prostheses, such as the ones shown in Figure 2, are made to mimic the spring-like behavior of the human ankle complex, specifically the Achilles tendon, but their form factor is often made to resemble that of a quadrupedal animal. Using this “cheetah” architecture, lower-limb amputees have been able to achieve new athletic heights, inching closer to Olympic levels (see Table 2).

In addition, alignment and residual limb to prosthesis attachment continue to be problems for amputee athletes. No matter how advanced prostheses become, they are useless without suitable means to attach and align them. To address the first issue, Burkett et al. studied alignment for transfemoral amputee runners, showing that lowering the knee joint improves running velocity and symmetry. New, more intimately attaching sockets have been produced to address the second issue. Madigan and Fillauer designed the 3-S Socket, a silicon suction socket made for both the upper and lower limbs. Further, Tingleff and Jensen made an adjustable socket from carbon and polyaramid fibers that uses a slit to form a flexible flap for readjustment. This socket is made to offer versatility for multiple sports, which require different socket fits. In all cases, the alignment and socket adjustments were made to optimize athletic performance and fit.

Presently uncommon, powered running prostheses should become more common in the future. As of now, there is limited published work. However, Huff et al. developed a

![Figure 2. Passive lower-limb prostheses. A, Flex-Foot (Flex-Walk, Laguna Hills, CA, USA) (Modular III). B, Flex-Sprint I (Ossur, Reykjavik, Iceland). C, Flex-Sprint II (Ossur). D, Flex-Sprint III (Cheetah; Ossur). E, Flex-Run (Ossur). F, Symes-Sprint (Ossur). B to F, Specialized running prostheses. Adapted from Lechler and Lilja.](image-url)
running controller for a powered knee-ankle prosthesis capable of reproducing some key elements of healthy running. These sorts of devices are far from commercial use, but they will likely be the next wave of assistive devices for amputee athletes.

Jumping requires similar assistance as running for amputees. Spring-like propulsion is key. Many have studied the effects of common jumping/running prostheses on performance, comparing amputee jumpers with individuals with biological limbs. These studies have shown that amputees often replicate the techniques of biological limb jumpers but exhibit certain compensatory mechanisms and asymmetries that lead to reduced ability.

NONWHEELED SEATED SPORT

Seated sports are quite popular for AMCs. These activities are conducted either using no technology, such as seated volleyball, or using adaptive chairs, such as several Paralympic tossing events. Although nonwheeled seated technology substantially limits mobility, it does offer stability that is difficult to achieve with wheeled devices. This is essential for sports that require the athlete to form a stable base and toss an object, for example, shot put, discus throw, and javelin.

As previously mentioned, some track-and-field competitions require seated technology. Specifically, the throwing sports require adaptive seats called throwing frames. Limited academic research has been conducted on these devices, but some have made attempts at analyzing them to determine advantageous configurations for competition and classification. However, neither of these studies provides conclusive evidence to improve athlete performance. Others have developed more adjustable throwing frames, which are hoped to enhance training and performance.

Fishing is another example of a seated sport that requires technology manipulations. This has been a significant point of innovation, particularly among independent inventors. Mechanisms have been developed to assist in holding the fishing rod, casting, and reeling. Examples of these modifications are shown in Figure 3. For chair users and those with upper-limb deficiencies, rod stability, power, and control are critical issues. More recent advances continue to tackle these problems.

SNOW AND ICE MOBILITY

Snow and ice activities are extremely popular among AMCs. For decades, adaptive equipment has been created to account for these conditions. These adaptations include outriggers/ski-tipped crutches to stabilize, stirrups for leg support, adaptive cuffs for persons with upper-arm conditions, modified boots and ski attachments for maneuverability, and sit skis with kayak-style poles for athletes with more severe conditions. Skiing prostheses typically focus on facilitating knee and ankle movement while establishing stability. Sit skis (Figure 4), on the other hand, are designed to maintain center of mass stability and inertia, often using adjustable frames. These adjustments influence both stability and comfort.

Prostheses for snowboarding are similar to those for skiing. Versatile leg movement is key. Joint rotation, in all planes, is essential. Minnoye and Plettenburg developed a transfibial snowboarding prosthesis capable of passive inversion/eversion and plantarflexion/dorsiflexion to make amputee snowboarding more comparable with snowboarding with biological limbs. Similarly, St-Jean and Goyette developed a passive multi-axis springed ankle prosthesis for ice skating to improve mobility for a 7-year-old figure skater. Robust multi-axis joint prostheses are difficult to build, but they are critical for athletic performance, especially activities that involve snow or ice mobility.

AQUATIC MOBILITY

Competitive swimming is commonly performed without assistance. One example is the S3 classification, commissioned by the IPC, which allows athletes with amputations of all four limbs to compete against one another. However, there does exist technology designed specifically to assist AMCs in swimming.

Swimming prostheses (see Figure 5) typically take the form of fin-like attachments, and many are designed to simplify navigating the poolside. Some have attempted to improve upon these by making more versatile feet. Colombo et al. built a leg capable of both walking and swimming. The approach described was an adaptable pylon ankle prosthesis capable of being manipulated into a fin-like configuration. Figure 5B shows this adaptation. Yoneyama et al. on the other hand,
developed an upper-limb prosthesis for above-elbow amputees to better achieve balance. This group used a simulation of the crawl stroke and an optimization method to build the upper-limb prosthesis.

Rowing is particularly difficult for athletes with upper-limb conditions. For amputees, these difficulties have been combated in a few ways. Rowing hands must maintain grasp and control on the paddle while mimicking human wrist ability. Highsmith et al. studied two such examples, determining that the one, the TRS kayak hand (Hammerhead Kayak Terminal Device, TRS Inc., Boulder, CO, USA), was forgiving of technical errors in paddling form and the other, the USF kayak hand (University of South Florida), maintained grasp better. In 2008, adaptive rowing became a Paralympic event, enabling athletes with physical conditions to compete in rowing competitions using adapted boats. These boats often

Figure 4. Sit ski. Sit skis are generally used by athletes with reduced lower-limb function and stability. Adapted from Cavacece et al.

Figure 5. Swimming prostheses. A, Swimming prostheses must be waterproof and durable. Fin-like attachments are used to improve leg thrust (top). Durable, rubber attachments with flat bases are used to aid in poolside navigation (bottom). B, An ankle prosthesis conforms to both walking and swimming. The swimming configuration angles the pylon to be better equipped for water thrust (bottom). Adapted from Saadah and Colombo et al.
include restraints, customizable seats, and gripping aids to facilitate rowing for AMCs.100

**DISCUSSION AND CONCLUSIONS**

Assistive technology ranges from simple to complicated, and it alone does not dictate athletic performance; however, along with training enhancements, medical advances, the increasing popularity of the Paralympics, and several other factors, it does play a large role in allowing AMCs to compete at the highest level. As para-sports progress, we will continue to see technological advances in assistive devices and athletes pushing the boundaries of physical limitations, further blurring the line between what people commonly consider “disabled” and what they do not. Thus far, assistive devices have been key in producing new levels of performance: lower-limb amputees are competing with Olympic athletes, Paralympic records are dropping more rapidly than ever, and wheelchair athletes have even surpassed some Olympic records. However, there are limitations.

A look back at the event and record comparisons in Tables 1 and 2 reveals the major limitation of state-of-the-art assistive technologies for sports. Wheelchairs are by far the most advanced and widely used devices, as evidenced by the number of wheelchair sports in the Paralympics and their positive impact on records; however, even these are vastly limited. Wheelchairs confine height, reach, and agility. Despite their constraints, wheelchairs clearly outperform other devices for most Paralympic events. Prostheses may be a better option going into the future, but as of now, they do not offer the versatile movement capabilities of wheelchairs.

Assistive sports devices have not yet begun to take advantage of smart and/or powered technology. Unlike daily-use wheelchairs and prostheses that are becoming smarter by incorporating electronics, sport devices continue to rely on advanced materials and mechanical designs. This lack could be either due to the ethics/purity of sports or due to the difficulty of producing powered devices suitable for the dynamic motions required for sports. Moving forward, powered devices may begin to arise in the same way as they have for general mobility. In addition, these devices will further exploit the interplay of biology and engineering, closely resembling biology and mimicking biological function. The goal of these advancements will be for AMCs to meet and surpass the abilities of competitors with no physical conditions.

Circling back to the original question—just how far can assistive technology enhancements take all athletes in the future—we now see that assistive devices have a long way to go before they can claim augmentative capabilities. However, the technology described in this article and used for present-day assistive devices does have implications in future athletic augmentation devices. Researchers have already begun to develop devices for the enhancement of dynamic movements.101,102 The progression of these devices is directly tied to that of assistive devices. As assistive technology for athletes competing with a physical condition advances, so will augmentative technology for athletes without physical conditions, creating the athlete of the future.

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